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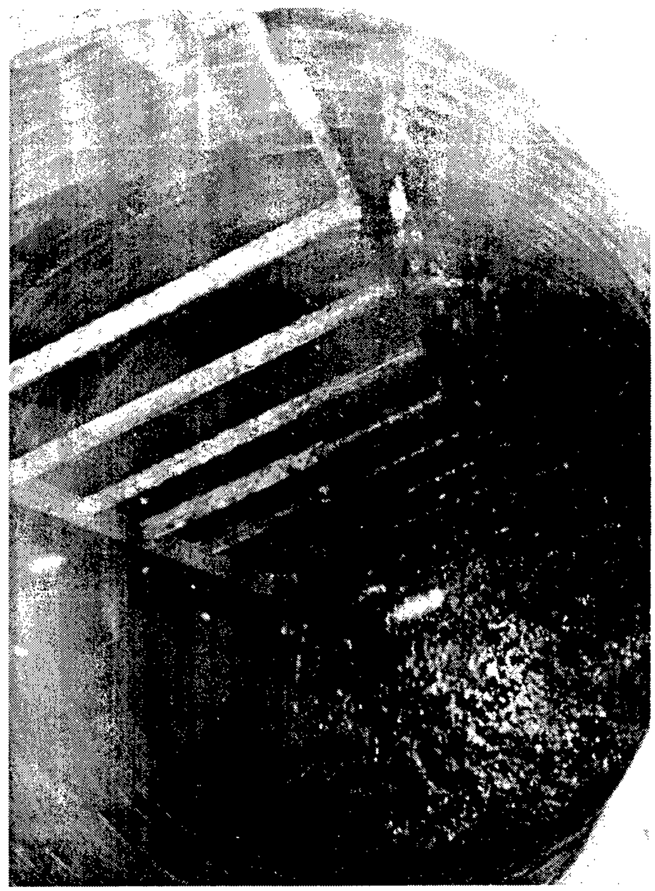
Boiling Manhole Heat-Loss Calculations

by
Charles P. Marsh and Terrill R. Laughton



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Estimates of the energy cost for several sample calculations of typical manholes are included. Using current Army "Red Book" energy costs, typical flooded manholes can cost the DoD between $50,000 and $125,000 per year if they remain unrepaired.

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Foreword

This study was conducted for U.S. Army Center for Public Works under Reimbursable Work Unit EI3, "Develop ECIP Guidance." The technical monitor was Dennis Vevang, CECPW-EM.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). Dr. Ilker R. Adiguzel is Acting Chief, CECER-FL-M, and Donald F. Fournier is Acting Operations Chief, CECER-FL.

COL James A. Walter is Commander of USACERL and Dr. Michael J. O'Connor is Director.

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1 Introduction

Background

Many DoD facilities own and operate heat distribution systems consisting of networks of underground piping and manholes connecting various buildings to a central high-temperature hot-water or steam supply. A key component of the efficiency of a heat distribution system is the amount of unrecoverable energy lost during transmission through the network of piping and manholes. In general, manholes degrade faster and require more maintenance than other components in a heat distribution system. A poorly maintained manhole has a large potential for heat loss. A variety of manhole designs and sizes can be found on DoD facilities and their degradation adversely affects the entire system. This report provides a method for analyzing the heat loss from a flooded manhole based on several characteristic components of a specific manhole. A simple correlation is developed that can easily be used in the field to estimate the manhole heat loss. A set of correlations involving either three or four key parameters has been developed to provide the heat loss estimates. The flooded manhole is the worst case scenario for heat loss.

Objectives

The overall objective of the project is to develop a set of correlations that can be used in the field to estimate the heat loss from a boiling manhole for an entire year. The heat-loss estimate is then used to assess the economic impact on the operations cost of the heat distribution system. The associated process of accelerated manhole component degradation and the adverse effects on maintenance and repair costs is not considered in this report.

Approach

The key parameters in the model are systematically varied over the relevant ranges and applied to the governing equations. A heat-loss vlaue is obtained using an iterative solution procedure. A regression analysis is performed on the calculated heat loss against

the input parameters. The results of the regression analysis determine the set of heat-loss correlations.

Mode of Technology Transfer

It is recommended that the results of this study be incorporated into an Engineer Technical Letter (ETL) and be published in the *Public Works Digest*. Incorporation of this information into or revision of the existing technical manual TM 5-810-17, *Heating and Cooling Distribution Systems*, and other operations and maintenance TMs, should be considered. The results of this study can also be integrated into existing Engineered Management Systems (EMSs) being developed at USACERL.

2 Model Development

Problem Formulation

In this model the flooded manhole contains heat distribution piping with ground water and/or surface runoff sufficient to cover the heat-carrying pipes. The ground water can enter through cracks in the manhole walls, improperly sealed conduit penetrations, an open end plate drain in an unsound casing, leaks, faulty valve packing, and/or blowing steam traps. The presence of the water creates conditions for heat loss regardless of the source of the water. Figure 1 shows the configuration of a flooded manhole. Several assumptions are made to reduce the complexity of the problem while still retaining the key fundamental physical phenomena driving the heat loss.

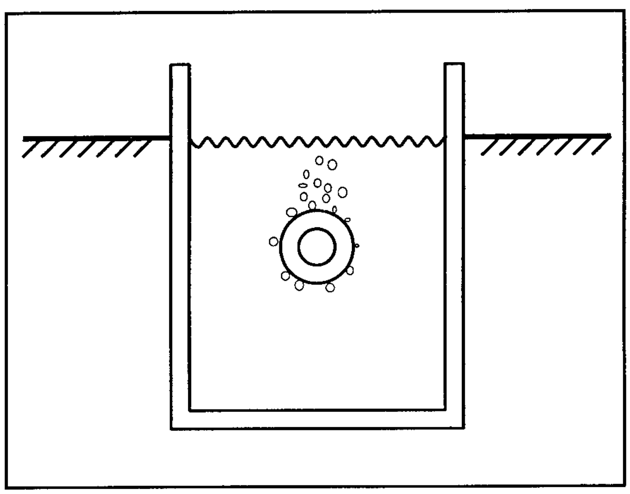


Figure 1. Configuration of boiling manhole

The main assumptions are:

- Nucleate boiling occurs on the full surface of all the submerged heat pipes.
- The heat pipe is always fully submersed in water.
- All of the steam generated by boiling is either condensed back into the fluid or escapes out of the manhole at atmospheric pressure.
- The orientation of the pipe is not considered important.
- The fluid temperature near the external pipe surface is considered to be at saturated conditions.
- There is no insulation or other restrictions to the heat flow away from the heat pipe.

As Figure 1 shows, hot water or steam flows through the center of the pipe. The latent heat from the fluid then conducts through the pipe wall and causes the water on the surface of the pipe to boil in the manhole. The heat is rejected to the water flooding the manhole by nucleate boiling. Figure 2 shows a diagram of the heat losses through the pipe.

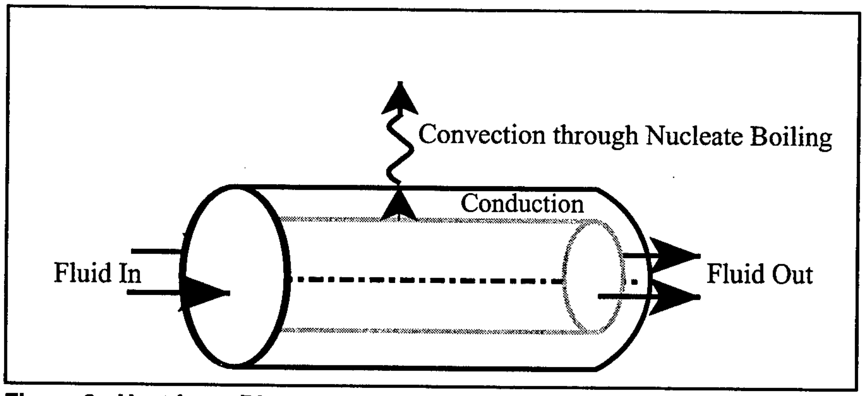


Figure 2: Heat Loss Diagram

High Temperature Hot Water

For the case in which the working fluid is high temperature hot water (HTHW), the total heat loss in the manhole is calculated by balancing the heat additions and the heat losses. The amount of heat put into the system (the pipe) is simply the difference in the latent heat of the water at the entrance and exit (Incropera and DeWitt 1990, p 481). The heat input can be expressed by:

$$Q = \dot{m} c_p \Delta T \qquad \text{[Eq 1]}$$

where,
Q = *heat loss* [W]
$\dot{m}$ = *mass flow* [kg/s]
c_p = *specific heat capacity* [J/kgK], *and*
$\Delta T = T_{in} - T_{out}$ [K].

The amount of heat leaving the system through the pipe walls will be the amount of heat that convects from the bulk fluid to the inside surface of the pipe, then conducts through the pipe walls and finally convects to the manhole water through nucleate boiling. The convection of the heat from the hot fluid to the inside surface of the pipe is governed by Newton's Law of cooling (Incropera and DeWitt 1990, p 476), and is given by:

$$Q = \pi D L h_c \Delta T \qquad \text{[Eq 2]}$$

where,
Q = heat loss [W]
D = inside diameter of pipe [m]
L = length of pipe [L]
h_c = convective heat transfer coefficient [W/m^{2}K], and
ΔT = the temperature difference between the pipe surface and saturation.

The convective heat transfer coefficient on the inside of the pipe surface is found from the Dittus-Boelter correlation (Dittus and Boelter 1930, p 443) which applies to turbulent flows through a smooth circular tube. The Dittus-Boelter correlation is given by:

$$h_c = 0.023\frac{k}{D}(Re_D)^{0.8}(Pr)^{0.3} \qquad \text{[Eq 3]}$$

where,
h_c = convective heat transfer coefficient [W/m^{2}K]
k = thermal conductivity [W/mK]
D = inside diameter of the pipe [m]
Re_D = Reynolds number in pipe [unitless], and
Pr = Prandtl number of the fluid [unitless].

Dry Steam

For the case in which the working fluid is steam, the total heat loss in the manhole is calculated by the difference between the inlet and exit quality. The inlet quality of the steam is assumed to be at 99%. A moisture content of 2% is generally considered commercially acceptable as dry steam. Field tests show that steam in district heating systems is well within this limit for low velocities (Diamant and Kut 1981, p 245). The value of 99% quality will be used as the entrance requirement into a boiling manhole at any point along a heat distribution system. With steam traps sufficiently placed throughout a steam distribution system to remove the condensate, this is a reasonable assumption. The amount of heat lost to the environment is determined by the difference in the steam quality at the entrance and exit of the boiling manhole and is given by:

$$Q = \dot{m}(x_i - x_o)h_{fg} \qquad \text{[Eq 4]}$$

where,
Q = heat loss [W]
$\dot{m}$ = mass flow [kg/s]
x_i = inlet quality [unitless]
x_o = outlet quality [unitless], and
h_{fg} = heat of vaporization [J/kg].

Condensate droplets will form in the vapor and deposit themselves on the pipe wall as a thin film. This condensate film provides a resistance between the vapor and the pipe surface (Incropera and DeWitt 1990, p 608). The thickness of the condensate layer inside the pipe will be assumed to be equal to the value of the total condensate mass that is formed through the length of the boiling manhole. The total condensate mass is assumed to be uniformly distributed on the inside surface of the pipe throughout the boiling section. This thickness will provide a *second* layer to the pipe. For purposes of conductive heat transfer, the pipe is thus treated as a composite system of two media. The heat transfer coefficient from the vapor to the film surface on the inside of the pipe is calculated from the following correlation (Cary 1992, p 471):

$$\frac{h}{h_{lo}} = (1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{(P/P_{cr})^{0.38}} \qquad \text{[Eq 5]}$$

where,
h = *the heat transfer coefficient* [W/m^2K]
h_{lo} = *Dittus-Boelter correlation* [W/m^2K]
x = *quality* [*unitless*]
P = *pressure at manhole* [*Pa*], *and*
P_{cr} = *critical pressure* [*Pa*].

The thickness of the condensate film is determined by finding the total amount of vapor that condenses in the pipe and deposits on the pipe surface. The total amount of condensing vapor is given by:

$$M = \frac{\dot{m}(x_{in} - x_{out})L}{v} \qquad \text{[Eq 6]}$$

where,
M = *total mass of condensate* [*kg*]
$\dot{m}$ = *mass flow* [*kg/s*]
x_{in} = *inlet quality* [*unitless*]
x_{out} = *outlet quality* [*unitless*]
L = *total length* [*m*], *and*
v = *velocity of steam* [*m/s*].

In order to determine the uniform thickness of the condensate layer, the condensate is assumed to be a hollow cylinder of uniform thickness. The thickness of the condensate layer is found by:

$$t = \frac{M}{\rho \pi D_{id} L} \qquad \text{[Eq 7]}$$

where,
t = *condensate thickness layer* [*m*]
M = *total mass of condensate* [*kg*]
ρ = *density of condensate liquid* [kg/m^3]
D_{id} = *average inside pipe diameter* [*m*], *and*
L = *total pipe length* [*m*].

Once the thickness of the condensate is known, the total heat conducted through the condensate film layer is given by:

$$Q = \frac{2\pi Lk(T_2 - T_1)}{\ln\left(\frac{r_{id}}{r_{id} - t}\right)} \qquad \text{[Eq 8]}$$

where,
Q = *heat loss* [*W*]
L = *total length of pipe* [*m*]
k = *thermal conductivity* [*W/mK*]
t = *thickness of the condensate layer* [*m*]
r_{id} = *inside radius of the pipe* [*m*]
T_2 = *temperature on the inside condensate layer* [*K*], *and*
T_1 = *temperature on the inside pipe surface* [*K*].

The conduction of heat through a pipe wall (Incropera and DeWitt 1990, p 98) uses the following equation for both the steam case and the HTHW case:

$$Q = \frac{2\pi Lk(T_2 - T_1)}{\ln(r_{od}/r_{id})} \qquad \text{[Eq 9]}$$

where,
Q = *heat loss* [*W*]
L = *total length of pipe* [*m*]
k = *thermal conductivity* [*W/mK*]
r_{od} = *outside radius of the pipe* [*m*]
r_{id} = *inside radius of the pipe* [*m*]
T_2 = *temperature on the inside pipe surface* [*K*], *and*
T_1 = *temperature on the outside pipe surface* [*K*].

The removal of heat from the surface of the pipe is assumed to be by nucleate boiling. Nucleate boiling generally exists when the temperature of the surface of the heating element is 5 °C over the saturation temperature of the fluid (Incropera and DeWitt 1990,

p 593). The difference in temperature between the surface of the pipe and the water in the relevant temperature ranges for this study all meet this requirement. The manhole water near the surface of the pipe is assumed to be at saturation. This assumption is based on the idea that as water vapor escapes from the manhole, new water will be allowed to enter the manhole and mix sufficiently. This will keep the bulk temperature at or near the saturation point. The heat loss from nucleate boiling (Incropera and DeWitt 1990, pp 596-597) can be expressed by:

$$q''_s = \mu_l h_{fg}\left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{.5}\left(\frac{c_{p,l}\Delta T}{C_{s,f} h_{fg} Pr_l}\right)^3 \qquad \text{[Eq 10]}$$

where,
q''_s = *heat loss flux* [W/m^2]
μ_l = *viscosity of the liquid* [Ns/m^2]
h_{fg} = *heat of vaporization* [J/kg]
g = *acceleration of gravity* [m/s^2]
ρ_l = *density of the liquid* [kg/m^3]
ρ_v = *density of the vapor* [kg/m^3]
σ = *surface tension of the liquid* [N/m^2]
$c_{p,l}$ = *specific heat of the liquid* [$J/(kgK)$]
$C_{s,f}$ = *surface-material coefficient equal to* 0.0130
Pr_l = *Prandtl number of the liquid* [*unitless*], *and*
ΔT = *the temperature difference between the pipe surface and saturation* [K].

Solution Method

High Temperature Hot Water

The solution for estimating the heat loss from a boiling manhole involves an iterative approach. Because all heat gains and heat losses must balance through every step of the solution process, the methodology is straightforward. The values that must be known or estimated by the user are:

- the temperature at the inlet of the manhole
- the velocity of the fluid at the entrance of the pipe
- the total length of the pipe in the manhole
- the average outside diameter of all the piping in the manhole.

Given these four parameters, a solution algorithm will model the manhole as one pipe of constant diameter immersed in water. The first step is to estimate the temperature on the surface of the pipe. With this initial estimate, the amount of heat lost by the manhole through nucleate boiling on the surface is calculated. The inside pipe temperature is then adjusted to balance with the conduction through the pipe, the convection on the inside surface of the pipe, and the loss of the latent heat in the fluid. Once the convective heat

transfer coefficient on the inside surface of the pipe is known, the *average* temperature of the water inside the pipe can be calculated, and once the average temperature of the water inside the pipe and the temperature at the entrance is known, the total heat loss from the manhole can be calculated. If this value is not within a specified tolerance of the original calculated heat loss value, a new value is chosen for the outside surface temperature of the pipe and the calculation is repeated. The process is continued until the new value and the old value converge. All the fluid properties are evaluated at saturation conditions inside the manhole and at an estimated 450 Kelvin (350.33 °F) inside the pipe.

Dry Steam

The solution process for the dry steam case is fundamentally the same as the HTHW case, with several important differences. The heat-loss estimates are still implemented in an iterative fashion with all the heat gains and heat losses balanced through every step in the solution process. However, the values that must be known or estimated by the user are now:

- the average pressure in piping of the boiling manhole
- the velocity of the steam in the entrance pipe
- the total length of the pipe in the manhole
- the average outside diameter of all the pipe in the manhole.

Given these four parameters, a solution algorithm will model the manhole as one pipe of constant diameter immersed in water. The first step in the solution algorithm is to estimate the exit quality of the steam. With this estimate, the amount of heat lost in the manhole is calculated by Equation 4. Once this value is known, the heat transfer coefficient on the inside surface of the condensate is calculated. The temperature on the condensate surface is then evaluated by Equation 2. Conduction through both the condensate layer and the pipe give the value on the outside surface of the pipe. After conduction through the condensate and pipe wall is calculated, the nucleate boiling heat transfer coefficient is calculated and another value of the total system heat loss is determined. The steam quality at the exit is adjusted in an iterative fashion until the heat loss from the condensation formation and the heat loss from the nucleate boiling on the outside surface are within a specified tolerance. All the vapor and fluid properties inside the pipe are evaluated at saturation. The properties are found by various polynomial and power fits to steam-table data (Incropera and DeWitt 1990, pp A22-A23). All the correlations use twelve data points and are valid between 0.10133 MPa (14.7 psia) and 1.455 MPa (211 psia). The following correlations are used for this purpose:

$$T_{sat}(P) = -68.23(P)^4 + 258.74(P)^3 - 368.25(P)^2 + 281.2(P) + 349.1 \qquad \text{[Eq 11]}$$

$$h_{fg}(P) = 161.29(P)^4 - 620.1(P)^3 + 900.04(P)^2 - 748.48(P) + 2322.2 \qquad \text{[Eq 12]}$$

$$v_f(P) = -0.0470(P)^4 + 0.182(P)^3 - 0.2655(P)^2 + 0.2344(P) + 1.0228 \qquad \text{[Eq 13]}$$

$$v_v(P) = 0.1944(P)^{-0.9415} \qquad \text{[Eq 14]}$$

$$cp_f(P) = -0.0444(P)^4 + 0.1487(P)^3 - 0.2129(P)^2 + 0.3342(P) + 4.1856 \qquad \text{[Eq 15]}$$

$$cp_v(P) = -0.2496(P)^4 + 0.8615(P)^3 - 1.1463(P)^2 + 1.2125(P) + 1.9178 \qquad \text{[Eq 16]}$$

$$\mu_f(P) = 252.12(P)^4 - 918.7(P)^3 + 1209.1(P)^2 - 728.93(P) + 337.38 \qquad \text{[Eq 17]}$$

$$\mu_v(P) = -2.8256(P)^4 + 10.665(P)^3 - 14.995(P)^2 + 10.998(P) + 11.091 \qquad \text{[Eq 18]}$$

$$k_f(P) = -58.542(P)^4 + 211.07(P)^3 - 267.8(P)^2 + 120.1(P) + 671.3 \qquad \text{[Eq 19]}$$

$$k_v(P) = -5.8316(P)^4 + 22.36(P)^3 - 31.544(P)^2 + 26.024(P) + 22.473 \qquad \text{[Eq 20]}$$

$$Pr_f(P) = -1.795(P)^4 - 6.4992(P)^3 + 8.4294(P)^2 - 4.8622(P) + 2.1274 \qquad \text{[Eq 21]}$$

$$Pr_v(P) = -0.0846(P)^4 + 0.3561(P)^3 - 0.5546(P)^2 + 0.4919(P) + 0.9408 \qquad \text{[Eq 22]}$$

where,
T_{sat} = *the saturation temperature (K)*
h_{fg} = *the heat of vaporization (kJ/kg)*
v_f = *the specific volume of the liquid* (m^3/kg)
v_v = *the specific volume of the vapor* (m^3/kg)
cp_f = *the specific heat of the liquid* (Ns/m^2)
cp_v = *the specific heat of the vapor* (Ns/m^2)
μ_f = *the viscosity of the liquid* (Ns/m^2)
μ_g = *the viscosity of the vapor* (Ns/m^2)
k_f = *the thermal conductivity of the fluid (W/mK)*
k_v = *the thermal conductivity of the vapor (W/mK)*
Pr_f = *the Prandtl number of the liquid (unitless), and*
Pr_v = *the Prandtl number of the vapor (unitless).*

Table 1 contains the R^2 values for all of the curve fits. The R^2 represents the goodness of fit of the curve. An R^2 value typically ranges from 0 to 1. An R^2 value of 1 means that the proportion of the total variation in the data is perfectly described by the model (Dobson 1983, p 50).

Table 1. R^2 value of thermodynamic curve fits

Thermodynamic Correlation	R^2 Value
Saturation Temperature of the Fluid	0.9997
Heat of Vaporization of the Fluid	0.9998
Specific Volume of the Fluid	0.9999
Specific Volume of the Vapor	1.0000
Specific Heat of the Fluid	0.9999
Specific Heat of the Vapor	1.0000
Viscosity of the Fluid	0.9974
Viscosity of the Vapor	0.9994
Thermal Conductivity of the Fluid	0.9909
Thermal Conductivity of the Vapor	0.9990
Prandtl Number of the Fluid	0.9946
Prandtl Number of the Vapor	0.9996

3 Correlation Development

To develop a usable and accurate correlation, a nonlinear, curve-fitting model is implemented using the four input variables (total length, average outside diameter, entrance temperature, and average velocity). The data are fit to a correlation that has the following form:

$$y = e^{\beta_0} x_1^{\beta_1} x_2^{\beta_2} \ldots x_n^{\beta_n} \qquad \text{[Eq 23]}$$

where,
y = the dependent variable
x = the independent variales
n = the number of independent variables, and
β = the parameters to be determined.

By taking the natural logarithm of both sides of Equation 23, the problem can be linearized (Freund and Minton 1979, pp 185-186) to an equation in the following form:

$$\ln[y] = \beta_0 + \beta_1 \ln[x_1] + \beta_2 \ln[x_2] + \ldots + \beta_n \ln[x_n]. \qquad \text{[Eq 24]}$$

Now a linear regression is performed to evaluate the β parameters which are then substituted back into Equation 24.

High Temperature Hot Water

To achieve an accurate correlation, an entire matrix of problems must be solved. All four parameters are varied independently of each other and the corresponding heat loss calculated. The temperature is varied between 130° and 190°C in 10°C increments. The velocity is varied between 0.5 and 3.0 m/s in 0.5 m/s increments. The diameter is set at the following nominal pipe sizes: 2, 2.5, 3, 3.5, 4 , 5, 6, 8, 10 inches. The length is set at 2, 4, 8, 12, 16 and 20 meters. With all these variations 2268 data points are obtained.

A typical HTHW system utilized by an army installation would have a minimum velocity of 2 ft/s (0.6096 m/s) and a maximum velocity of about 7 ft/s (2.1336 m/s). A typical nominal velocity is about 5 ft/s (1.5240 m/s). The minimum allowable nominal pipe size

is 1.5 in. with pipe sizes of 6 in. and larger for long delivery systems (Army Technical Manual [TM] 5-810-2, p 3-1). Standard supply temperatures from a HTWH system range from 320 to 440 °F (160 to 226.7 °C) (TM 5-810-2, p 1-1). Standard return water temperatures are from 250 to 275 °F (121.1 to 135 °C) as a minimum (TM 5-810-2, p 2-2). A flooded manhole can be found at a temperature range anywhere between the typical supply temperature and the typical return temperature. The standard thermodynamic ranges utilized by the HTHW heating systems are well represented in the development of the heat loss correlations.

Dry Steam

In order to achieve an accurate correlation, an entire matrix of problems must be solved. All four parameters are varied independently of each other and the corresponding heat loss calculated. The pressure is varied from 0.2 MPa to 1.4 MPa (29.0 psia to 203.1 psia) in 0.2 MPa (29.0 psia) increments. The velocity is varied from 55.0 m/s to 80.0 m/s (180.4 ft/s to 262.5 ft/s) in 5.0 m/s (14.4 ft/s) increments. The diameter is set at the following nominal pipe sizes (NPS): 2, 2.5, 3, 3.5, 4 , 5, 6, 8, 10 in. The length is set at 2, 4, 8, 12, 16 and 20 m. With all these variations 2268 data points are obtained.

A dry steam system utilized for heat distribution has a low-pressure range below 44.7 psia (0.308 MPa), a medium-pressure range between 44.7 psia and 139.7 psia (0.308 MPa and 0.963 MPa), and a high-pressure range above 139.7 psia (0.963 MPa) (Diamant 1981, pp 237-238). A typical maximum velocity is between 200 and 250 ft/sec (60.96 m/s and 76.2 m/s) (Diamant 1981, p 244).

4 Results

High Temperature Hot Water

The power fit correlation for metric units in the form of Equation 23 is:

$$\text{Heat Loss} = 0.01409[T]^{3.2534}[L]^{0.9320}[V]^{0.3553}[D]^{0.7372} \quad \text{[Eq 25]}$$

where...
T = *inlet temperature* [°*C*]
L = *total length* [*m*]
V = *average velocity* [*m/s*], *and*
D = *average outside pipe diameter* [*m*].

Equation 25 gives the value of the heat loss in Watts. *The equation is only valid for the units specified above.* The average error in the equation is ±8.8%. The error is determined by:

$$\text{Error} = \frac{\text{Correlation Value} - \text{Calculated Value}}{\text{Calculated Value}} \quad \text{[Eq 26]}$$

The largest errors are obtained when using very low average diameters. If the average diameter used is 2 in. NPS then the errors reach as high as 48%.

The power fit correlation for English units is:

$$\text{Heat Loss} = 0.000090209[T]^{3.5383}[L]^{0.9300}[V]^{0.3610}[D]^{0.7652} \quad \text{[Eq 27]}$$

where,
T = *inlet temperature* [°*F*]
L = *total length* [*ft*]
V = *average velocity* [*ft/s*], *and*
D = *average outside pipe diameter* [*ft*].

The Heat Loss in Equation 27 is given in BTU/hr. *Again, the equation is valid only for the units specified above.*

Equation 27 provides the best accuracy for the heat loss in a boiling manhole if the input parameters are accurately determined or estimated. The most uncertain and difficulty

to estimate parameter is the average fluid velocity. If the average fluid velocity is not known or difficult to estimate, a set of three different correlations can be used to determine heat loss in the flooded manhole. The set of three correlations are broken down into three different velocity regimes: *high, medium, and low*. For the three different velocity regimes the velocities are fixed at a characteristic velocity. The three characteristic velocities are:

- High = 5 ft/s [1.5240 m/s]
- Medium = 3.5 ft/s [1.0668 m/s]
- Low = 2 ft/s [0.6096 m/s].

The characteristic velocity that best represents the average velocity determines the appropriate correlation to use. At this point there are only three parameters to be determined by the user to estimate the heat loss in the flooded manhole. The three correlations are as follows:

For Metric Units

High Velocity Range

$$\text{Heat Loss} = 0.01839921835[D]^{0.7071916}[L]^{0.9283152}[T]^{3.2607392} \quad \text{[Eq 28]}$$

Medium Velocity Range

$$\text{Heat Loss} = 0.0001779524416[D]^{0.8555449}[L]^{0.897267}[T]^{3.54102192} \quad \text{[Eq 29]}$$

Low Velocity Range

$$\text{Heat Loss} = 0.02863[D]^{0.9320}[L]^{0.8653}[T]^{3.1849} \quad \text{[Eq 30]}$$

where,
Heat Loss = heat loss from pipe [*W*]
D = average outside pipe diameter [*m*]
L = total pipe length [*m*], *and*
T = inlet temperature [°*C*].

For English Units

High Velocity Range

$$\text{Heat Loss} = 0.00016263[D]^{0.8025}[L]^{0.9158}[T]^{3.5629} \quad \text{[Eq 31]}$$

Medium Velocity Range

$$\text{Heat Loss} = 0.00017795[D]^{0.8555}[L]^{0.8972}[T]^{3.5410} \quad \text{[Eq 32]}$$

Low Velocity Range

$$\textit{Heat Loss} = 0.00020183[D]^{0.9419}[L]^{0.8656}[T]^{3.5051} \qquad \text{[Eq 33]}$$

where,
Heat Loss = *heat loss from pipe [BTU/hr]*
D = *average outside pipe diameter [ft]*
L = *total pipe length [ft], and*
T = *inlet temperature [°F].*

The errors associated with Equations 28 through 33 vary, and reflect the difference between the correlation and the actual calculated value from the model. No experimental verification has been performed to validate the models. Error percentages are given in Table 2.

Table 2. HTHW correlation error percentages.

	Percentage Errors	
	Average Error (%)	Maximum Error (%)
General Metric Correlation	12.2%	78.6%
General English Correlation	12.1%	73.2%
Low Velocity Metric Correlation	9.57%	41.9%
Low Velocity English Correlation	9.49%	44.9%
Medium Velocity Metric Correlation	9.88%	38.1%
Medium Velocity English Correlation	9.86%	41.2%
High Velocity Metric Correlation	10.2%	35.8%
High Velocity English Correlation	10.2%	38.8%

The largest errors generally occur when the total length of pipe in the manhole is small (around 2 m). In general, a larger percentage error results when input parameters approach the extremes of the heat loss correlation. The parameter ranges for all the correlations are:

- Input Temperature: 130 to 190°C [266 to 374°F]
- Total Pipe Length: 2 to 20 m [6.56 to 65.6 ft]
- Average Outside Pipe Diameter: 0.0603 to 0.273 m [2.374 to 10.75 in.]

and, if the velocity is a free parameter:

- Average Pipe Velocity: 0.5 to 3.0 m/s [1.640 to 9.843 ft/s]

Dry Steam Case

The power fit correlation for metric units in the form of Equation 23 is,

$$\textit{Heat Loss} = 196622.3[P]^{1.0243}[L]^{0.9561}[V]^{0.1758}[D]^{0.6173} \qquad \text{[Eq 34]}$$

where,
P = inlet pressure [MPa]
L = total length [m]
V = average velocity [m/s], and
D = average outside pipe diameter [m].

Equation 34 gives the value of the heat loss in Watts. *The equation is only valid for the units specified above.* The average error in the equation is ±8.8%. The largest errors are obtained when using very low average diameters. If the average diameter used is 2 in. (nominal pipe size) errors can reach as high as 48%.

The power fit correlation for English units is:

$$\textit{Heat Loss} = 591.8765[P]^{1.0243}[L]^{0.9561}[V]^{0.1758}[D]^{0.6173} \qquad \text{[Eq 35]}$$

where,
P = inlet pressure [psia]
L = total length [ft]
V = average velocity [ft/s], and
D = average outside pipe diameter [ft].

The Heat Loss in Equation 35 is given in BTU/hr. *Again, the equation is valid only for the units specified above.*

Equations 34 and 35 provide the best accuracy for the heat loss in a boiling manhole if the input parameters are accurately determined or estimated. The parameter with the most uncertainty is the system pressure at the location of the boiling manhole. If the pressure drop in the system is relatively uniform, an estimate of the pressure drop can be made by obtaining the pressure at the system's inlet and return line. This gives a measured value of the pressure drop through the entire system. A linear approximation of the pressure drop at the boiling manhole can then be made by estimating the manhole's location in the distribution system. For example, if the manhole is located halfway down the distribution system, then half of the pressure drop can be estimated to have occurred. Subtracting this relative pressure-drop estimate from the inlet pressure will give an estimate of the local pressure at the boiling manhole. The average fluid velocity can be estimated as the inlet velocity to the distribution system. If the velocity is not known or is difficult to estimate, a set of three different correlations can

be used to determine the heat loss in the flooded manhole. The set of three correlations are broken down into three different velocity regimes: *high, medium, and low*. For the three different velocity regimes the velocities are fixed at a characteristic velocity. The three characteristic velocities are:

- High = 262.5 ft/s [80.0 m/s]
- Medium = 205.1 ft/s [67.5 m/s]
- Low = 180.4 ft/s [55.0 m/s].

The characteristic velocity that best represents the average velocity determines the appropriate correlation to use. At this point there are only three parameters to be determined by the user to estimate the heat loss in the flooded manhole. The three correlations are:

For Metric Units

High Velocity Range

$$\text{Heat Loss} = 452019.2[D]^{0.6369}[L]^{0.9351}[P]^{0.9851} \quad \text{[Eq 36]}$$

Medium Velocity Range

$$\text{Heat Loss} = 456954.9[D]^{0.6501}[L]^{0.9279}[P]^{0.9845} \quad \text{[Eq 37]}$$

Low Velocity Range

$$\text{Heat Loss} = 463179.5[D]^{0.6674}[L]^{0.9186}[P]^{0.9843} \quad \text{[Eq 38]}$$

where,
Heat Loss = heat loss from pipe [W]
D = average outside pipe diameter [m]
L = total pipe length [m], and
P = inlet pressure [MPa].

For English Units

High Velocity Range

$$\text{Heat Loss} = 1769.781[D]^{0.6369}[L]^{0.9351}[P]^{0.9851} \quad \text{[Eq 39]}$$

Medium Velocity Range

$$\text{Heat Loss} = 1781.46[D]^{0.6501}[L]^{0.9279}[P]^{0.9845} \quad \text{[Eq 40]}$$

Low Velocity Range

$$Heat\ Loss = 1789.62[D]^{0.6674}[L]^{0.9186}[P]^{0.9843} \quad \text{[Eq 41]}$$

where,
Heat Loss = *heat loss from pipe* [*Btu/hr*]
D = *average outside pipe diameter* [*ft*]
L = *total pipe length* [*ft*], *and*
P = *inlet pressure* [*psia*].

The errors associated with Equations 36 through 41 vary, and reflect the difference between the correlation and the actual calculated value from the model. Error percentages are given in Table 3.

Table 3. Dry steam correlation percentage errors.

	Percentage Errors	
	Average Error (%)	Maximum Error (%)
General Metric Correlation	14.4%	50.4%
General English Correlation	14.4%	50.4%
Low Velocity Metric Correlation	14.1%	53.2%
Low Velocity English Correlation	14.1%	53.2%
Medium Velocity Metric Correlation	14.3%	51.1%
Medium Velocity English Correlation	14.3%	51.1%

In general, a larger percentage error results when the input parameters approach the extremes of the power correlation. The parameter ranges for all the correlations are:

- Input Pressure: 0.2 to 1.4 MPa [29.0 to 203.1 psia]
- Total Pipe Length: 2 to 20 m [6.56 to 65.6 m]
- Average Outside Pipe Diameter: 0.0603 to 0.273 m [2.374 to 10.75 in.]

and, if the velocity is a free parameter:

- Average Fluid Velocity: 55.0 to 80.0 m/s [180.4 to 262.5 ft/s].

Sample Calculations

This section contains a set of eight sample calculations using the correlations developed for estimating heat loss from a continuously boiling manhole. The calculations demonstrate the method involved to properly estimate manhole heat loss during a field calculation given limited information. Although the required input parameters may be difficult to estimate in some cases, it is important to estimate the quantities as accurately as possible. The input parameters in the sample calculations given below, although typical, are not meant to be used on any specific type of manhole. There are four sample calculations for the HTHW and four sample calculations for the dry steam case. Each sample calculation is presented in both English and metric units.

Example 1a: HTHW General Correlation, Metric Units

A heat distribution system is found to have a boiling manhole. The average velocity through the piping is estimated at 4 ft/s. By bleeding off the high temperature hot water the temperature at the entrance of the manhole is found to be 163°C. The total pipe length in the manhole is 14 ft and the average outside diameter of the piping is known to be 4 in.

Step 1: Unit Consistency

Once all parameter values are determined, it is imperative to put them into the proper units. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Temperature	163 °C	(none)	163 °C
Length	14 ft	convert ft to m (multiply by 0.3048)	4.2672 m
Velocity	4 ft/s	convert ft/s to m/s (multiply by 0.3048)	1.2192 m/s
Outside Diameter	4 in.	convert in. to m (multiply by 0.0254)	0.1016 m

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[T]^{3.2534}$	$[163]^{3.2534}$	15,744,600
$[L]^{0.9320}$	$[4.2672]^{0.9320}$	3.866
$[V]^{0.3553}$	$[1.2192]^{0.3553}$	1.0730
$[D]^{0.7372}$	$[0.1016]^{0.7372}$	0.1853

Once all the expression values are calculated the complete correlation can be evaluated by Equation 25:

$$\textit{Heat Loss} = 0.01409\,[T]^{3.2534}\,[L]^{0.9320}\,[V]^{0.3553}\,[D]^{0.7372}$$

$$\textbf{Heat Loss} = (0.01409)\cdot(15744600)\cdot(3.866)\cdot(1.0730)\cdot(0.1853) \cong \textbf{171,000 Watts}$$

Example 1b: HTHW General Correlation, English Units

A heat distribution system is found to have a boiling manhole. The average velocity through the piping is estimated at 4 ft/s. By bleeding off the high temperature hot water the temperature at the entrance of the manhole is found to be 163°C. The total pipe length in the manhole is 14 ft and the average outside diameter of the piping is known to be 4 in.

Step 1: Unit Consistency

Once all parameter values are determined, it is imperative to put them into the proper units. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Temperature	163 °C	convert °C to °F (multiply by 9/5 add 32)	325.4 °F
Length	14 ft	(none)	14 ft
Velocity	4 ft/s	(none)	4 ft/s
Outside Diameter	4 in.	convert in. to ft (divide by 12)	0.3333 ft

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[T]^{3.5383}$	$[325.4]^{3.5383}$	775,688,000
$[L]^{0.9300}$	$[14]^{0.9300}$	11.639
$[V]^{0.3610}$	$[4]^{0.3610}$	1.6495
$[D]^{0.7652}$	$[0.3333]^{0.7652}$	0.4314

Once all the expression values are calculated the complete correlation can be evaluated by Equation 27:

$$Heat\ Loss = 0.000090209\ [T]^{3.5383}\ [L]^{0.9300}\ [V]^{0.3610}\ [D]^{0.7652}$$

$$\textbf{Heat Loss} = (0.000090209)\cdot(775688000)\cdot(11.639)\cdot(1.6495)\cdot(0.4314) \cong \textbf{580,000 Btu/hr}$$

Example 2a: HTHW High-Velocity Correlation, Metric Units

A boiling manhole has an average velocity through the piping typical of the high velocity range. The high temperature hot water at the entrance of the manhole is found to be 147 °C. The total pipe length in the manhole is 7 m and the average outside diameter of the piping is known to be 12 cm.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	12 cm	convert cm to m (divide by 100)	0.12 m
Length	7 m	(none)	7 m
Temperature	147 °C	(none)	147 °C

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.7916}$	$[0.12]^{0.7916}$	0.1867
$[L]^{0.9152}$	$[7.0]^{0.9152}$	5.935
$[T]^{3.2392}$	$[147]^{3.2392}$	10,480,300

Once all the expression values are calculated the complete correlation can be evaluated by Equation 28:

$$Heat\ Loss = 0.021835\ [D]^{0.7916}\,[L]^{0.9152}\,[T]^{3.2392}$$

$$\textbf{Heat Loss} = (0.021835)\cdot(0.1867)\cdot(5.935)\cdot(10480300) \cong \textbf{254,000 Watts}$$

Example 2b: HTHW High-Velocity Correlation, English Units

A boiling manhole has an average velocity through the piping typical of the high velocity range. The high temperature hot water at the entrance of the manhole is found to be 147 °C. The total pipe length in the manhole is 7 m and the average outside diameter of the piping is 12 cm.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	12 cm	convert cm to ft (multiply by 0.032808)	0.3937 ft
Length	7 m	convert m to ft (multiply by 3.2808)	22.966 ft
Temperature	147 °C	convert °C to °F (multiply by 9/5 add 32)	296.6 °F

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.8025}$	$[0.3937]^{0.8025}$	0.4733
$[L]^{0.9158}$	$[22.966]^{0.9158}$	17.639
$[T]^{3.5629}$	$[296.6]^{3.5629}$	642,834,000

Once all the expression values are calculated the complete correlation can be evaluated by Equation 31:

$$Heat\ Loss = 0.00016263\ [D]^{0.8025}\ [L]^{0.9158}\ [T]^{3.5629}$$

$$\textbf{Heat Loss} = (0.00016263)\cdot(0.4733)\cdot(17.639)\cdot(642834000) \cong \textbf{873,000 Btu/hr}$$

Example 3a: HTHW Medium-Velocity Correlation, Metric Units

A flooded manhole near the end of a heat-distribution system has an average velocity in the medium velocity range. The temperature at the inlet of the piping to the manhole is 278 °F. The average pipe diameter inside the manhole is 3 in. and the total length of pipe in the manhole is 11 ft.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted. Once all the parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	3 in.	convert in. to m (multiply by 0.0254)	0.0762 m
Length	11 ft	convert ft to m (multiply by 0.3048)	3.3528 m
Temperature	278 °F	convert °F to °C (subtract 32 and multiply by 5/9)	136.67 °C

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.8449}$	$[0.0762]^{0.8449}$	0.1136
$[L]^{0.8967}$	$[3.3528]^{0.8967}$	2.959
$[T]^{3.2192}$	$[136.67]^{3.2192}$	7,501,700

Once all the expression values are calculated the complete correlation can be evaluated by Equation 29:

$$\text{Heat Loss} = 0.024416\ [D]^{0.8449}\ [L]^{0.8967}\ [T]^{3.2192}$$

$$\textbf{Heat Loss} = (0.024416)\cdot(0.1136)\cdot(2.959)\cdot(7501700) \cong \textbf{61,600 Watts}$$

Example 3b: HTHW Medium-Velocity Correlation, English Units

A flooded manhole near the end of a heat-distribution system has an average velocity in the medium velocity range. The temperature at the inlet of the piping to the manhole is 278 °F. The average pipe diameter inside the manhole is 3 in. and the total length of pipe in the manhole is 11 ft.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the medium-velocity English units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	3 in.	convert in. to ft (divide by 12)	0.25 ft
Length	11 ft	(none)	11 ft
Temperature	278 °F	(none)	278 °F

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.8555}$	$[0.25]^{0.8555}$	0.3054
$[L]^{0.8972}$	$[11]^{0.8972}$	8.597
$[T]^{3.5410}$	$[278]^{3.5410}$	451,193,000

Once all the expression values are calculated the complete correlation can be evaluated by Equation 32:

$$\text{Heat Loss} = 0.00017795\ [D]^{0.8555}\ [L]^{0.8972}\ [T]^{3.5410}$$

$$\textbf{Heat Loss} = (0.00017795)\cdot(0.3054)\cdot(8.597)\cdot(451193000) \cong \mathbf{211{,}000\ Btu/hr}$$

Example 4a: HTHW Low-Velocity Correlation, Metric Units

A large heat-distribution system serving several large facilities and a few smaller buildings has a flooded manhole in its network. The velocity in the network is known to best fit the low-velocity range correlations. The temperature at the inlet to the manhole is relatively high at 185 °C and the total pipe length in the manhole is 19 ft. The average outside diameter is 6.5 in.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the low-velocity metric units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	6.5 in.	convert in. to m (multiply by 0.0254)	0.1625 m
Length	19 ft	convert ft to m (multiply by 0.3048)	5.791 m
Temperature	185 °C	(none)	185 °C

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.9320}$	$[0.1625]^{0.9320}$	0.1839
$[L]^{0.8653}$	$[5.791]^{0.8653}$	4.571
$[T]^{3.1849}$	$[185]^{3.1849}$	16,623,200

Once all the expression values are calculated the complete correlation can be evaluated by Equation 30:

$$\text{Heat Loss} = 0.02863\,[D]^{0.9320}\,[L]^{0.8653}\,[T]^{3.1849}$$

$$\textbf{Heat Loss} = (0.02863)\cdot(0.1839)\cdot(4.571)\cdot(16623200) \cong \textbf{400,000 Watts}$$

Example 4b: HTHW Low-Velocity Correlation, English Units

A large heat-distribution system serving several large facilities and a few smaller buildings has a flooded manhole in its network. The velocity in the network is known to best fit the low-velocity range correlations. The temperature at the inlet to the manhole is relatively high at 185 °C and the total pipe length in the manhole is 19 ft. The average outside diameter is 6.5 in.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the medium-velocity English units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	6.5 in.	convert in. to ft (divide by 12)	0.5417 ft
Length	19 ft	(none)	19 ft
Temperature	185 °C	convert °C to °F (multiply by 9/5 add 32)	365 °F

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.9419}$	$[0.5417]^{0.9419}$	0.5613
$[L]^{0.8656}$	$[19]^{0.8656}$	12.791
$[T]^{3.5051}$	$[365]^{3.5051}$	957,398,000

Once all the expression values are calculated the complete correlation can be evaluated by Equation 33:

$$\text{Heat Loss} = 0.00020183\,[D]^{0.9419}\,[L]^{0.8656}\,[T]^{3.5051}$$

$$\textbf{Heat Loss} = (0.00020183)\cdot(0.5613)\cdot(12.791)\cdot(957{,}398{,}000) \cong \mathbf{1{,}387{,}000\ Btu/hr}$$

Example 5a: Dry-Steam General Correlation, Metric Units

A heat-distribution system is found to have a boiling manhole. The average velocity of the steam through the piping is estimated at 230 ft/s. The pressure in the manhole is estimated at 0.9 MPa. The total pipe length in the manhole is 14 ft and the average outside diameter of the piping is 4 in.

Step 1: Unit Consistency

Once all the parameter values are known, it is imperative to put them into the proper units. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Pressure	0.9 MPa	(none)	0.9 MPa
Length	14 ft	convert ft to m (multiply by 0.3048)	4.2672 m
Velocity	230 ft/s	convert ft/s to m/s (multiply by 0.3048)	70.104 m/s
Outside Diameter	4 in.	convert in. to m (multiply by 0.0254)	0.1016 m

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[P]^{1.0243}$	$[0.9]^{1.0243}$	0.8977
$[L]^{0.9561}$	$[4.2672]^{0.9561}$	4.0039
$[V]^{0.1758}$	$[70.104]^{0.1758}$	2.1110
$[D]^{0.6173}$	$[0.1016]^{0.6173}$	0.2438

Once all the expression values are calculated the complete correlation can be evaluated by Equation 34:

$$\text{Heat Loss} = 196622.3\,[P]^{1.0243}\,[L]^{0.9561}\,[V]^{0.1758}\,[D]^{0.6173}$$

$$\textbf{Heat Loss} = (196622.3)\cdot(0.8977)\cdot(4.0039)\cdot(2.1110)\cdot(0.2438) \cong 364{,}000 \text{ Watts}$$

Example 5b: Dry-Steam General Correlation, English Units

A heat-distribution system is found to have a boiling manhole. The average velocity of the steam through the piping is estimated at 230 ft/s. The pressure in the manhole is estimated at 0.9 MPa. The total pipe length in the manhole is 14 ft and the average outside diameter of the piping is 4 in.

Step 1: Unit Consistency

Once all parameter values are determined, it is imperative to put them into the proper units. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Pressure	0.9 MPa	convert MPa to psia (multiply by)	130.53 psia
Length	14 ft	(none)	14 ft
Velocity	230 ft/s	(none)	230 ft/s
Outside Diameter	4 in.	convert in. to ft (divide by 12)	0.3333 ft

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[P]^{1.0243}$	$[130.53]^{1.0243}$	146.94
$[L]^{0.9561}$	$[14]^{0.9561}$	12.468
$[V]^{0.1758}$	$[230]^{0.1758}$	2.6013
$[D]^{0.6173}$	$[0.3333]^{0.6173}$	0.5075

Once all the expression values are calculated the complete correlation can be evaluated by Equation 35:

$$\text{Heat Loss} = 591.8765\, [P]^{1.0243}\, [L]^{0.9561}\, [V]^{0.1758}\, [D]^{0.6173}$$

$$\textbf{Heat Loss} = (591.8765)\cdot(146.94)\cdot(12.468)\cdot(2.6013)\cdot(0.5075) \cong \textbf{1,432,000 Btu/hr}$$

Example 6a: Dry-Steam High-Velocity Correlation, Metric Units

A boiling manhole supplied by a steam distribution system has an average velocity through the piping typical of the high-velocity range. The pressure of the saturated steam in the manhole is found to be 1.1 MPa. The total pipe length in the manhole is 7 m and the average outside diameter of the piping is 12 cm.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	12 cm	convert cm to m (divide by 100)	0.12 m
Length	7 m	(none)	7 m
Pressure	1.1 MPa	(none)	1.1 MPa

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6369}$	$[0.12]^{0.6369}$	0.2591
$[L]^{0.9351}$	$[7.0]^{0.9351}$	6.1695
$[P]^{0.9851}$	$[1.1]^{0.9851}$	1.0984

Once all the expression values are calculated the complete correlation can be evaluated by Equation 36:

$$\text{Heat Loss} = 452019.2\,[D]^{0.6369}\,[L]^{0.9351}\,[P]^{0.9851}$$

$$\textbf{Heat Loss} = (452019.2)\cdot(0.2591)\cdot(6.1695)\cdot(1.0984) \cong \textbf{794,000 Watts}$$

Example 6b: Dry-Steam High-Velocity Correlation, English Units

A boiling manhole supplied by a steam distribution system has an average velocity through the piping typical of the high-velocity range. The pressure of the saturated steam in the manhole is found to be 1.1 MPa. The total pipe length in the manhole is 7 m and the average outside diameter of the piping is 12 cm.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted. Once all the parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	12 cm	convert cm to ft (multiply by 0.032808)	0.3937 ft
Length	7 m	convert m to ft (multiply by 3.2808)	22.966 ft
Pressure	1.1 MPa	convert MPa to psia (multiply by 145.0377)	159.54 psia

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6369}$	$[0.3937]^{0.6369}$	0.5523
$[L]^{0.9351}$	$[22.966]^{0.9351}$	18.739
$[P]^{0.9851}$	$[159.54]^{0.9851}$	147.93

Once all the expression values are calculated the complete correlation can be evaluated by Equation 39:

$$\text{Heat Loss} = 1769.781\ [D]^{0.6369}\ [L]^{0.9351}\ [P]^{0.9851}$$

$$\textbf{Heat Loss} = (1769.781)\cdot(0.5523)\cdot(18.739)\cdot(147.93) \cong \textbf{2,710,000 Btu/hr}$$

Example 7a: Dry-Steam Medium-Velocity Correlation, Metric Units

A flooded manhole near the end of a heat distribution system has an average velocity in the medium velocity range. The average system pressure at the location of the manhole is 80 psia. The average pipe diameter inside the manhole is 3 in. and the total length of pipe in the manhole is 11 ft.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the high-velocity metric units correlation), the units must be converted.Once all parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	3 in.	convert in. to m (multiply by 0.0254)	0.0762 m
Length	11 ft	convert ft to m (multiply by 0.3048)	3.3528 m
Pressure	80 psia	convert MPa to psia (multiply by 0.0068948)	0.5516 MPa

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6501}$	$[0.0762]^{0.6501}$	0.1876
$[L]^{0.9279}$	$[3.3528]^{0.9279}$	3.0727
$[P]^{0.9845}$	$[0.5516]^{0.9845}$	0.5567

Once all the expression values are calculated the complete correlation can be evaluated by Equation 37:

$$\text{Heat Loss} = 456954.9\,[D]^{0.6501}\,[L]^{0.9279}\,[P]^{0.9845}$$

$$\textbf{Heat Loss} = (456954.9)\cdot(0.1876)\cdot(3.0727)\cdot(0.5567) \cong \textbf{147,000 Watts}$$

Example 7b: Dry-Steam Medium-Velocity Correlation, English Units

A flooded manhole near the end of a heat distribution system has an average velocity in the medium velocity range. The average system pressure at the location of the manhole is 80 psia. The average pipe diameter inside the manhole is 3 in. and the total length of pipe in the manhole is 11 ft.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the medium-velocity English units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	3 in.	convert in. to ft (divide by 12)	0.25 ft
Length	11 ft	(none)	11 ft
Pressure	80 psia	(none)	80 psia

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6501}$	$[0.25]^{0.6501}$	0.4061
$[L]^{0.9279}$	$[11]^{0.9279}$	9.2535
$[P]^{0.9845}$	$[80]^{0.9845}$	74.747

Once all the expression values are calculated the complete correlation can be evaluated by Equation 40:

$$\text{Heat Loss} = 1781.46\,[D]^{0.6501}\,[L]^{0.9279}\,[P]^{0.9845}$$

$$\textbf{Heat Loss} = (1781.46)\cdot(0.4061)\cdot(9.2535)\cdot(74.747) \cong \mathbf{500{,}000\ Btu/hr}$$

Example 8a: Dry-Steam Low-Velocity Correlation, Metric Units

A large heat distribution system serving several large facilities and a few smaller buildings has a flooded manhole in its network. The velocity in the network is known to best fit the low velocity range correlations. The manhole is relatively close to the central steam supply facility and has a relatively high estimated pressure of 1.2 MPa. The total pipe length in the manhole is 19 ft, and the average outside diameter is 6.5 in.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the low-velocity metric units correlation), the units must be converted. Once all the parameter values are reasonably well known, the units conversion can proceed. If the metric correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	6.5 in.	convert in. to m (multiply by 0.0254)	0.1625 m
Length	19 ft	convert ft to m (multiply by 0.3048)	5.7913 m
Pressure	1.2 MPa	(none)	1.2 MPa

Step 2: Calculation

Each input value is now plugged into the *metric* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6674}$	$[0.1625]^{0.6674}$	0.2974
$[L]^{0.9186}$	$[5.7913]^{0.9186}$	5.0198
$[P]^{0.9843}$	$[1.2]^{0.9843}$	1.1966

Once all the expression values are calculated the complete correlation can be evaluated by Equation 38:

$$\text{Heat Loss} = 463179.5\,[D]^{0.6674}\,[L]^{0.9186}\,[P]^{0.9843}$$

$$\textbf{Heat Loss} = (463179.5)\cdot(0.2974)\cdot(5.0198)\cdot(1.1966) \cong \textbf{827,000 Watts}$$

Example 8b: Dry-Steam Low-Velocity Correlation, English Units

A large heat distribution system serving several large facilities and a few smaller buildings has a flooded manhole in its network. The velocity in the network is known to best fit the low velocity range correlations. The manhole is relatively close to the central steam supply facility and has a relatively high estimated pressure of 1.2 MPa. The total pipe length in the manhole is 19 ft, and the average outside diameter is 6.5 in.

Step 1: Unit Consistency

After verifying that the proper correlation is being used, (the medium-velocity English units correlation), the units must be converted. Once all parameter values are reasonably well known, the units conversion can proceed. If the English correlation is used, then:

Parameter	Given Value	Conversion	Input Value
Outside Diameter	6.5 in.	convert in. to ft (divide by 12)	0.5417 ft
Length	19 ft	(none)	19 ft
Pressure	1.2 MPa	convert MPa to psia (multiply by 145.0377)	174.05 psia

Step 2: Calculation

Each input value is now plugged into the *English* correlation to determine heat loss. The values of the individual components are:

Expression	Plug in Initial Value	Expression Value
$[D]^{0.6674}$	$[0.5417]^{0.6674}$	0.6642
$[L]^{0.9186}$	$[19]^{0.9186}$	14.951
$[P]^{0.9843}$	$[174.05]^{0.9843}$	160.51

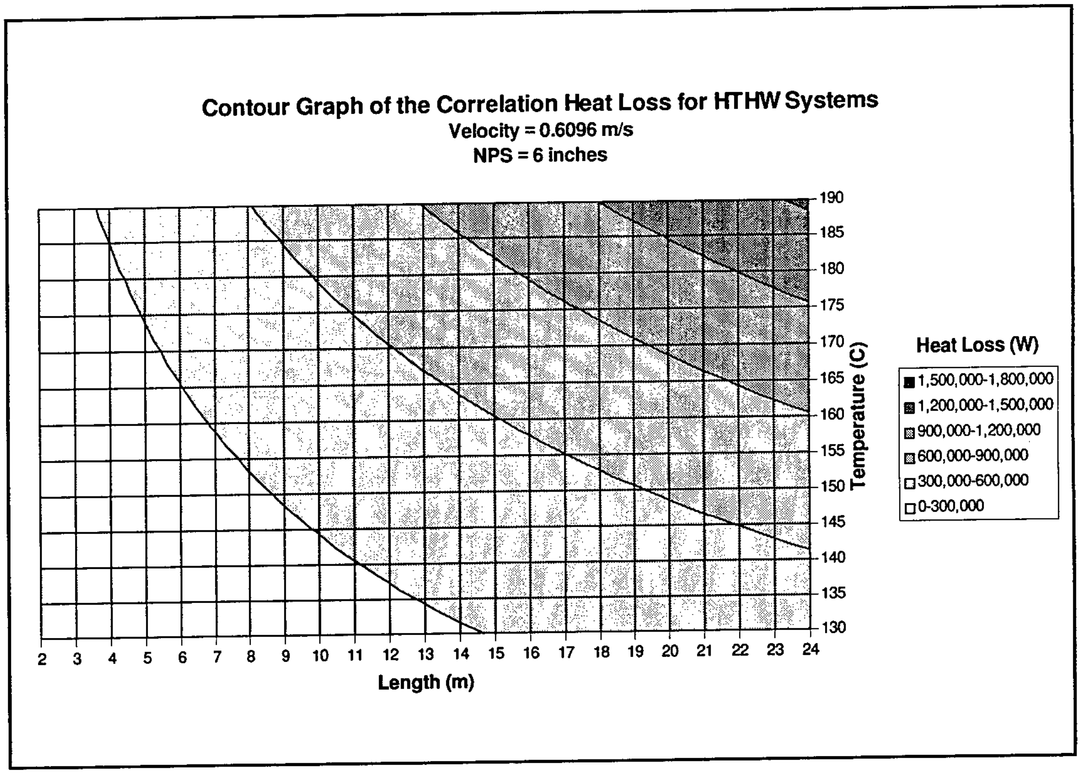
Once all the expression values are calculated the complete correlation can be evaluated by Equation 41:

$$\text{Heat Loss} = 1789.62\,[D]^{0.6674}\,[L]^{0.9186}\,[P]^{0.9843}$$

$$\textbf{Heat Loss} = (1789.62)\cdot(0.6642)\cdot(14.951)\cdot(160.51) \cong \textbf{2,853,000 Btu/hr}$$

Graphical Comparison

A graphical comparison of the fixed-velocity correlation heat losses and the actual heat losses are shown on the following six pages. The nominal pipe size (NPS) is fixed at 6 in. and the velocity is fixed at the appropriate rate. The graphical comparison demonstrates that the correlations accurately represent the calculated heat loss. For all the comparisons, the shape of the graphs and the ranges of the heat loss are in good agreement. The comparison graphs demonstrate that the correlations accurately represent the influence of the parameters on heat loss. In general, there is more deviation at the end values of the correlations than at the more intermediate ranges.



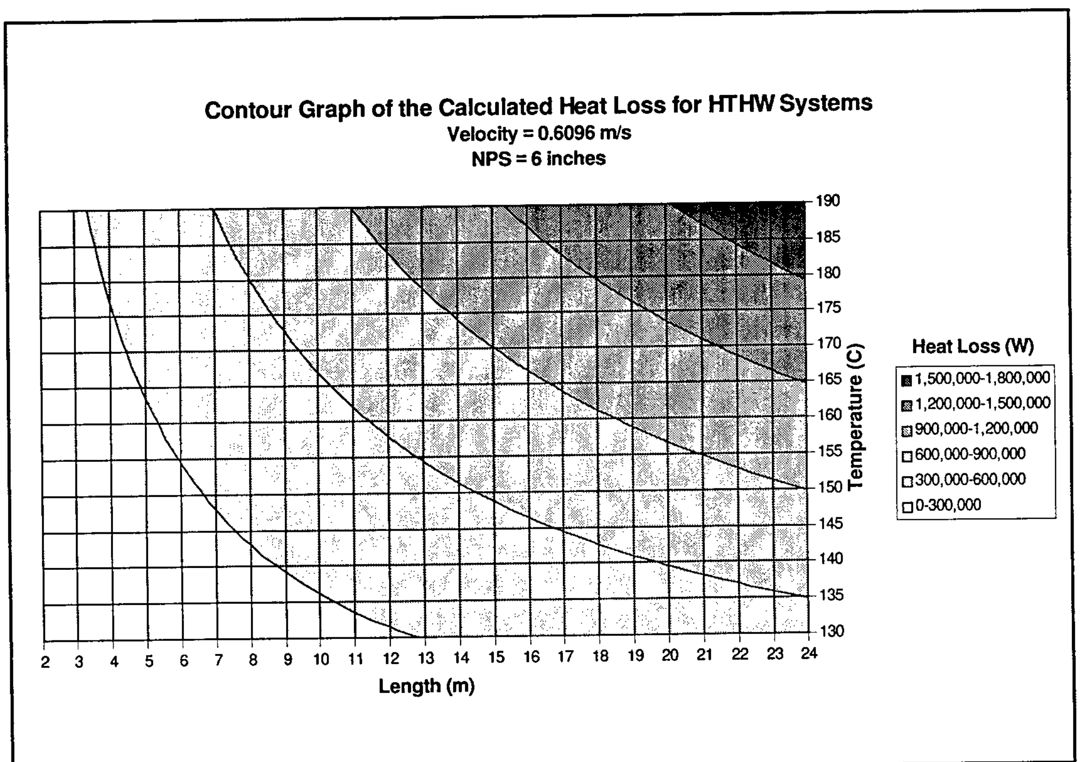
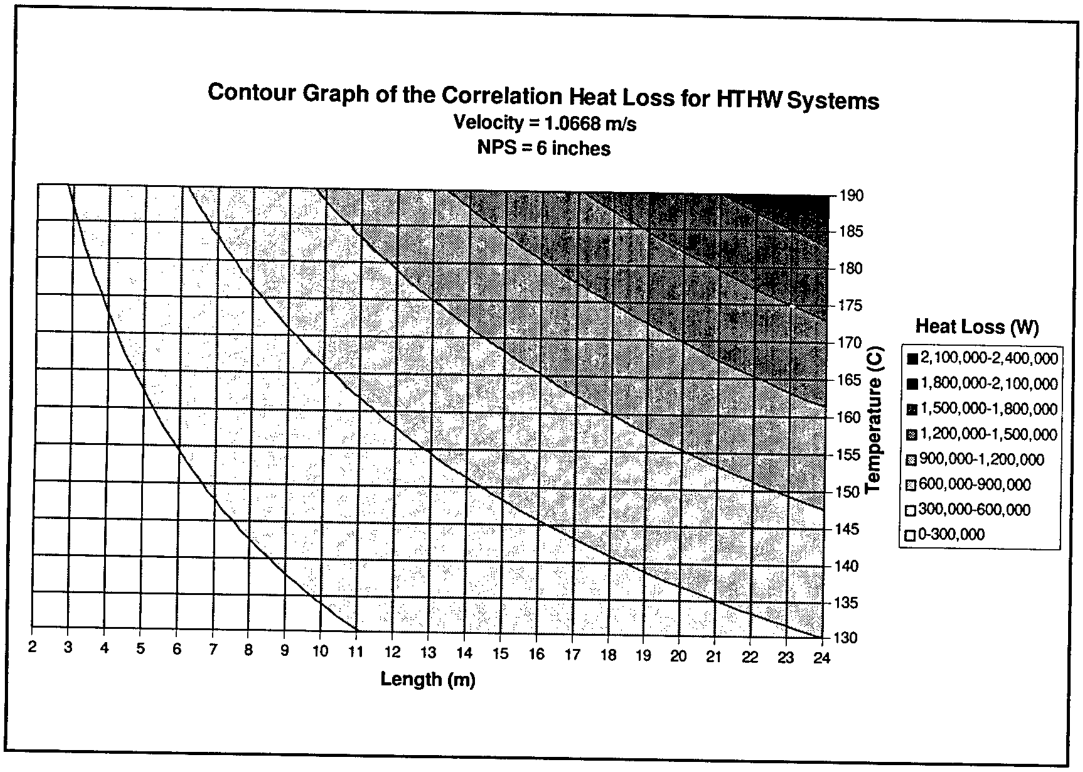


Figure 4. Comparison between correlation and calculated heat loss for low velocity.



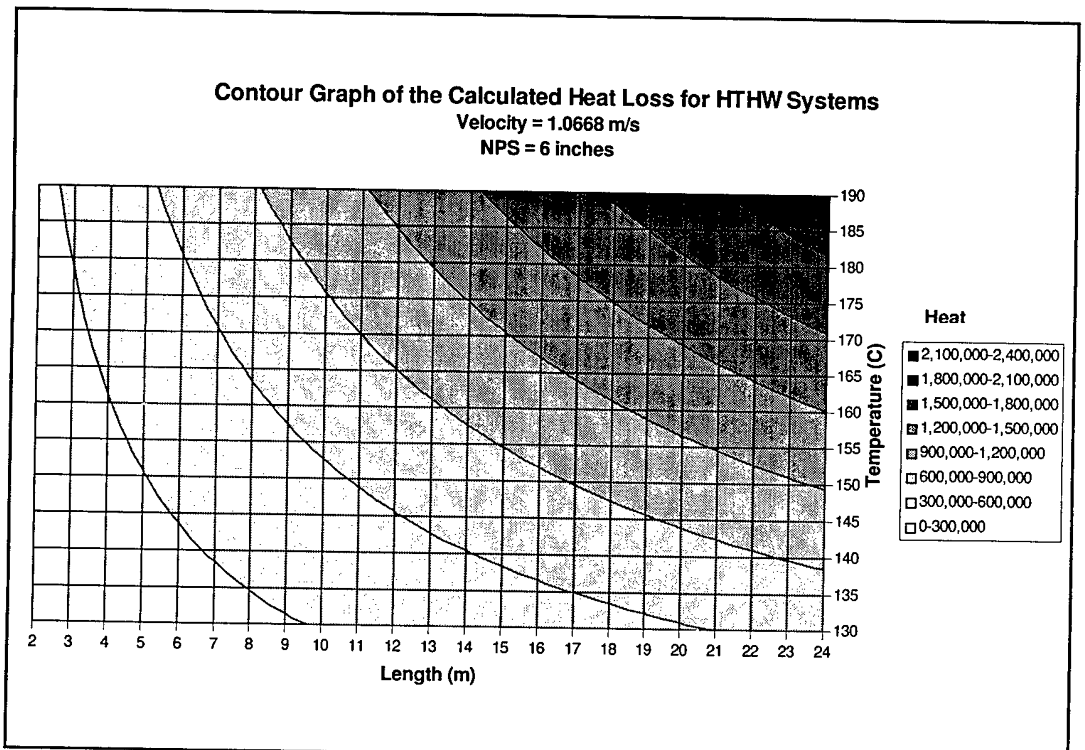
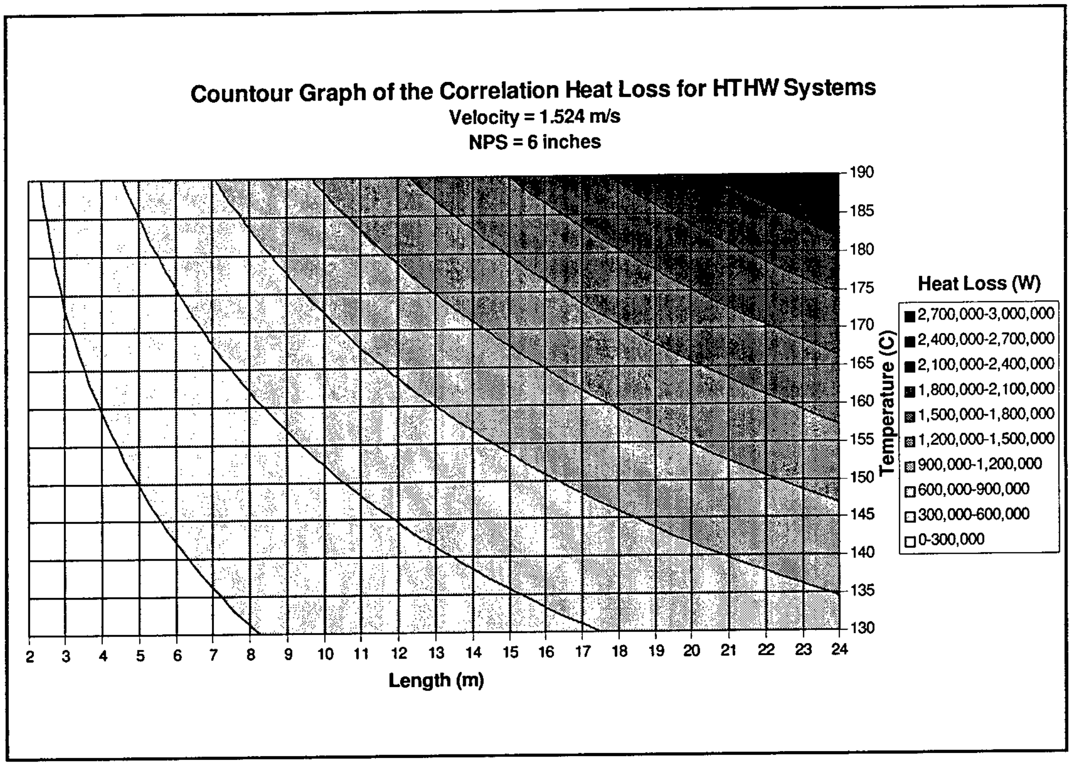


Figure 5. Comparison between correlation and calculated heat loss for medium velocity



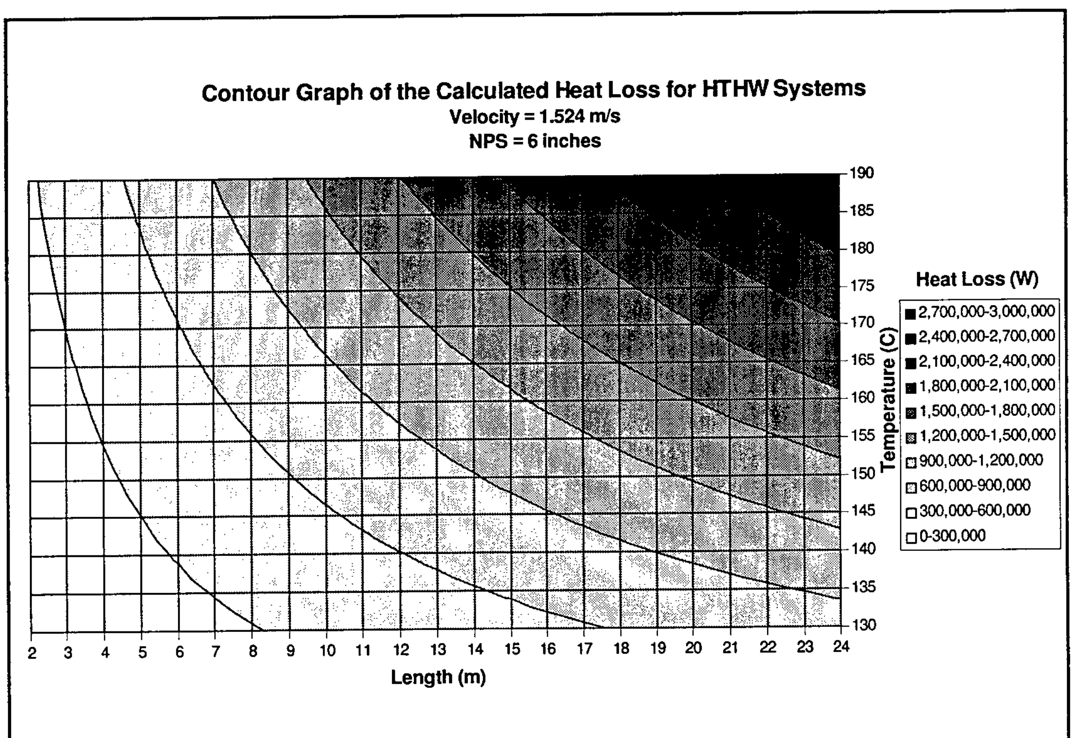
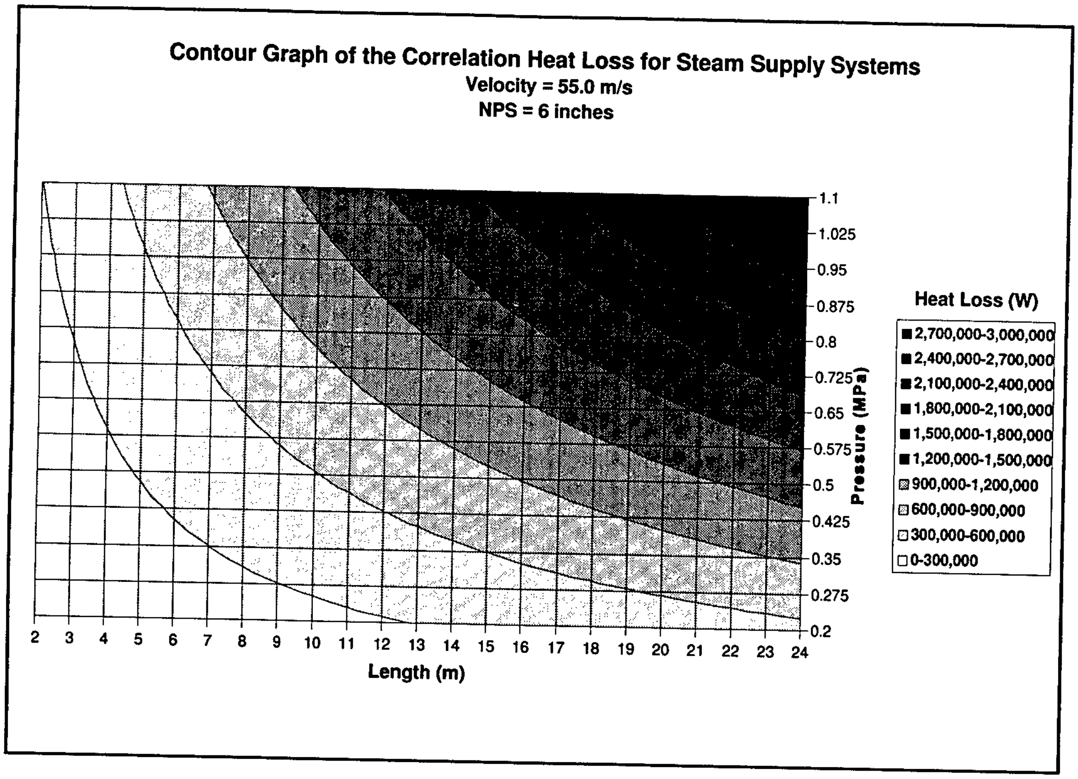


Figure 6. Comparison between correlation and calculated heat loss for high velocity.



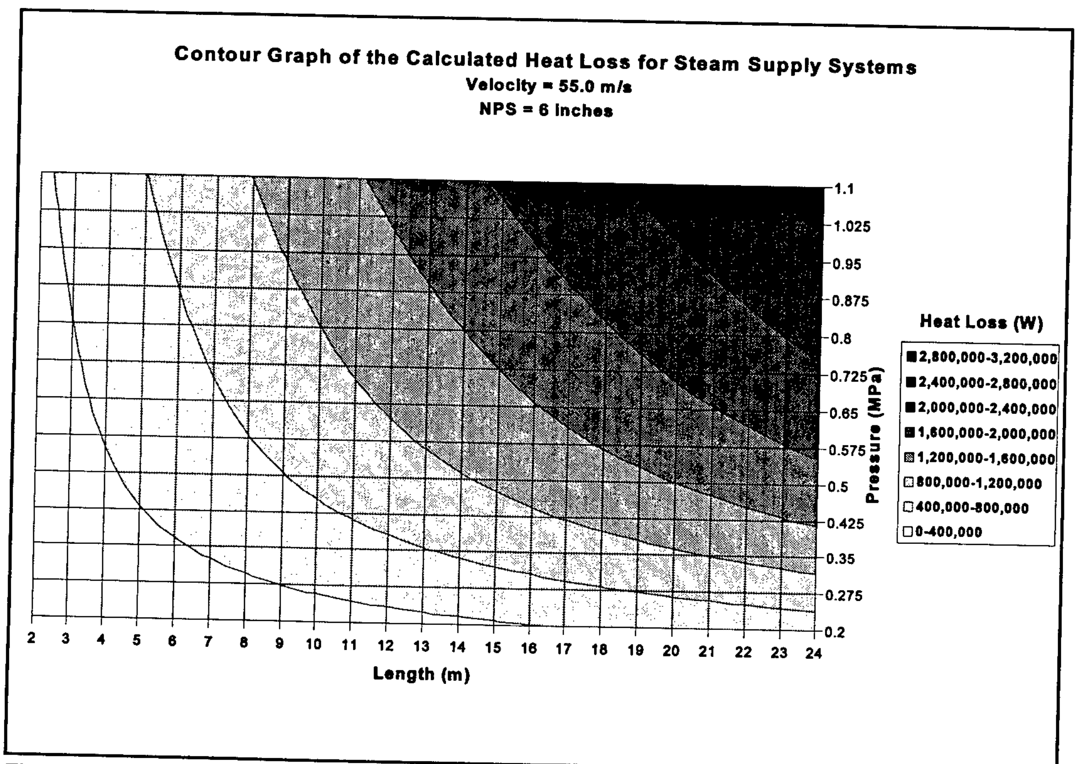
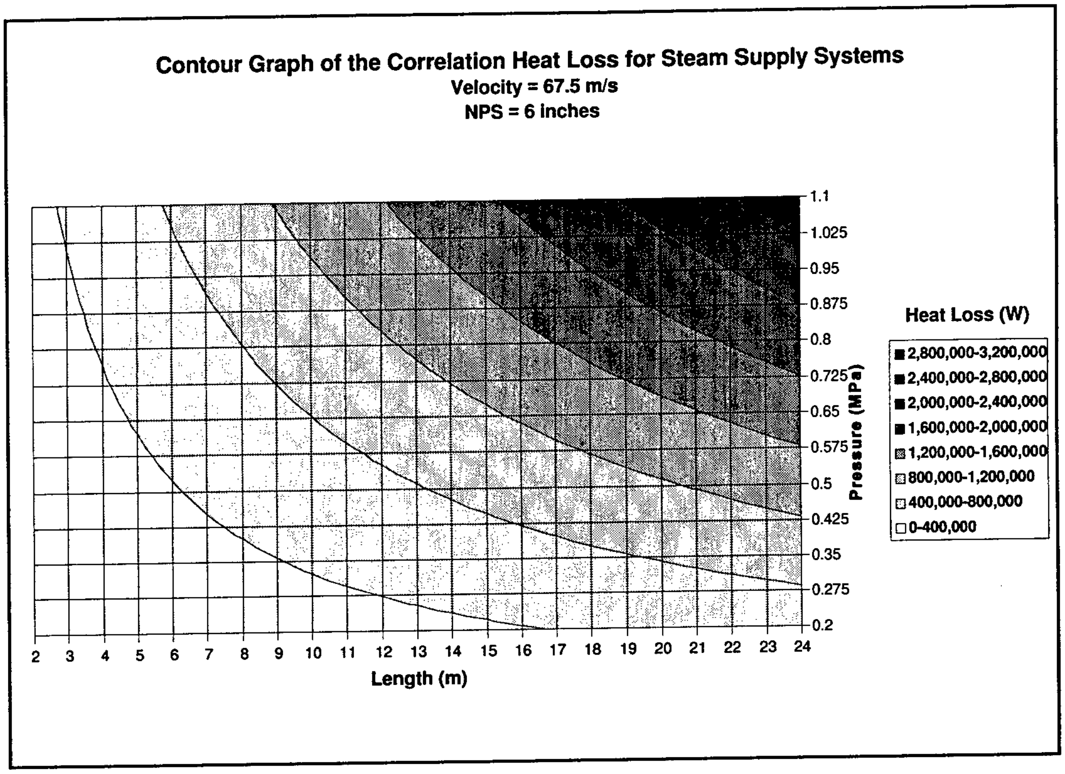


Figure 7. Comparison between correlation and calculated heat loss for low velocity.



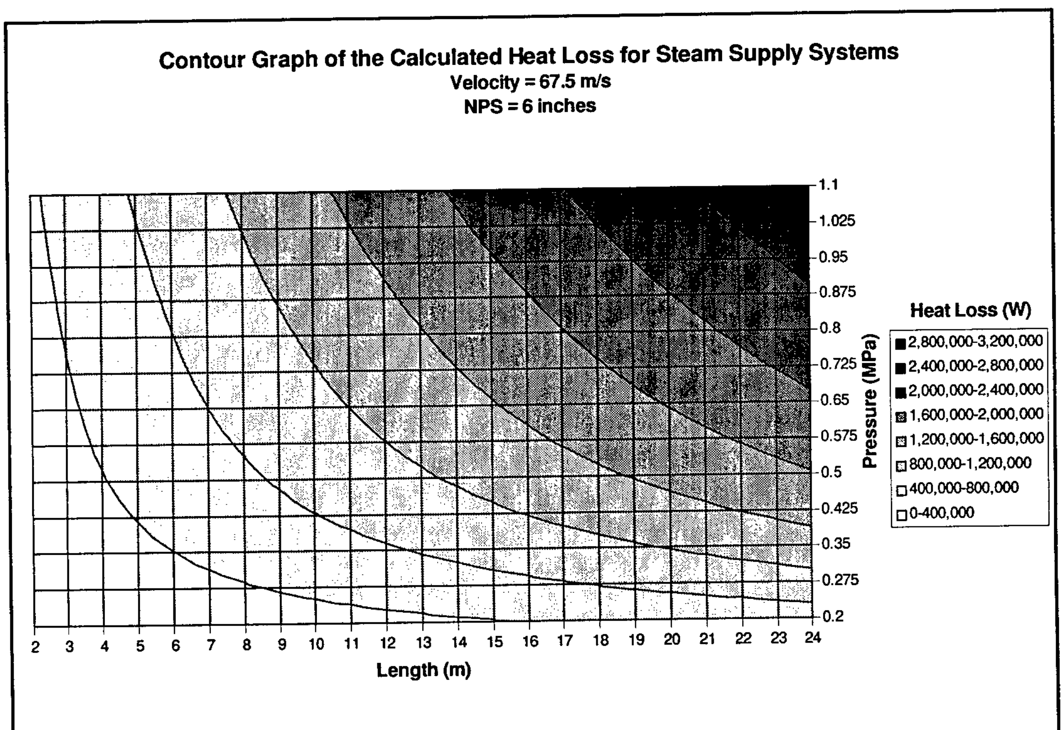
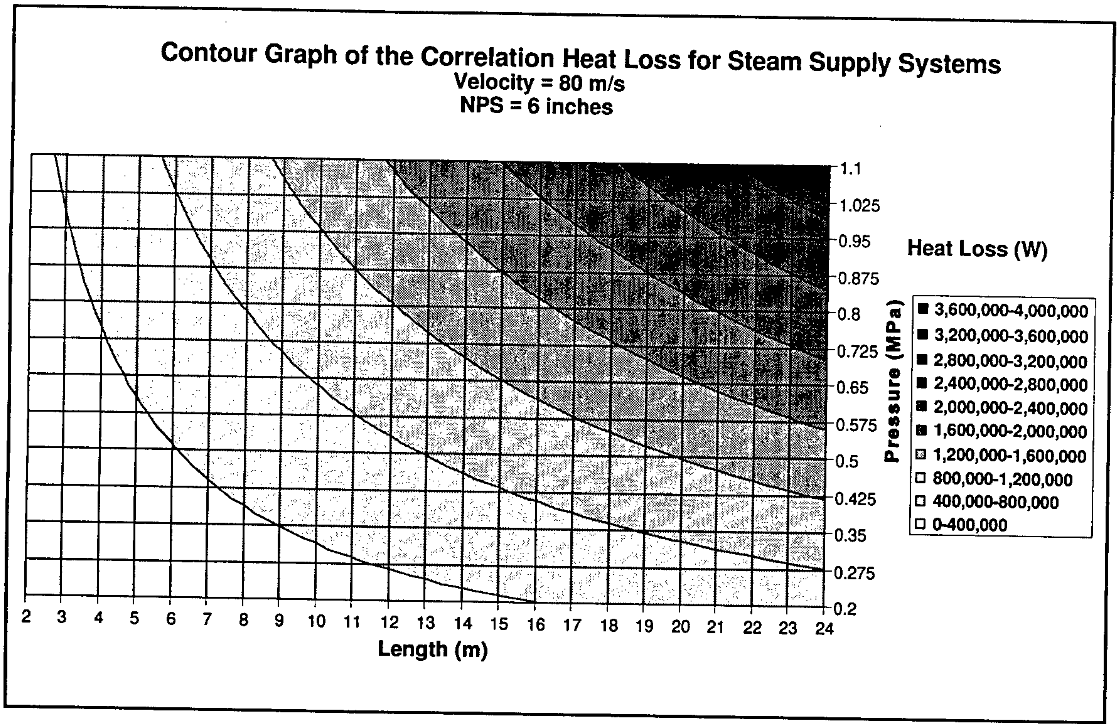


Figure 8. Comparison between correlation and calculated heat loss for medium velocity.



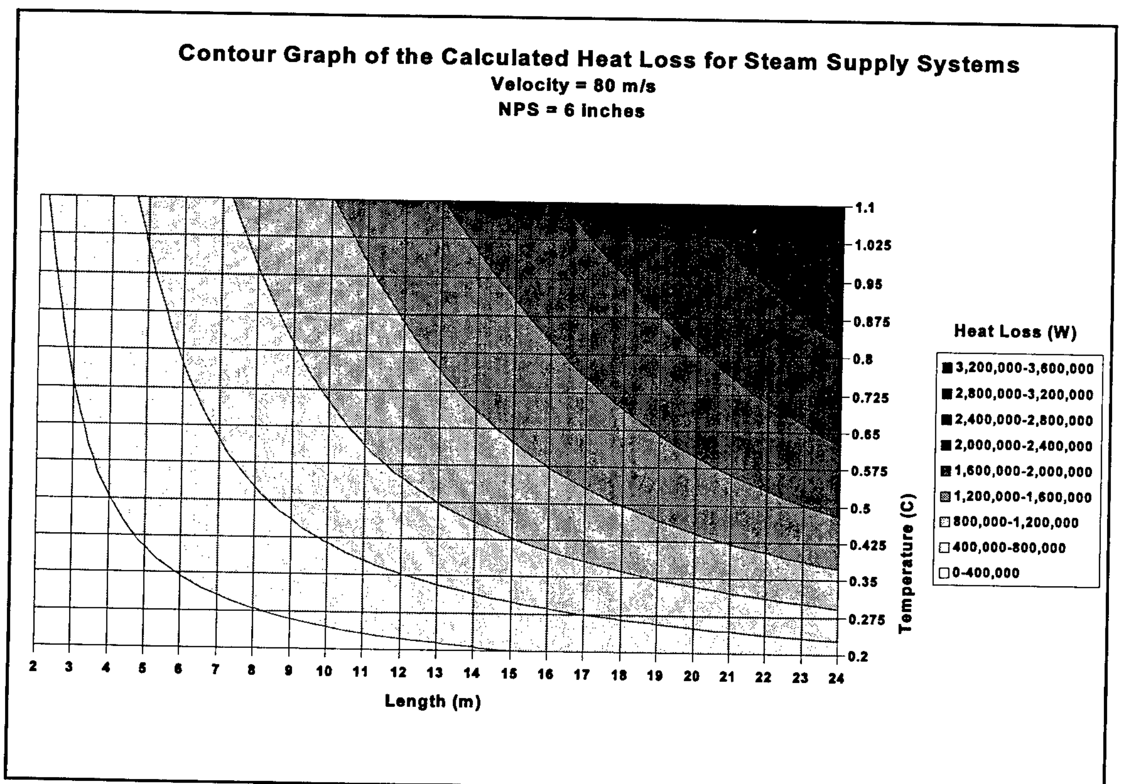


Figure 9. Comparison between correlation and calculated heat loss for high velocity.

5 Conclusions

This report provides a method for easily and accurately estimating the heat loss from a boiling manhole. The data requirements are minimal and the required calculations are relatively simple to perform. By selecting the appropriate correlation equations, personnel can quickly estimate heat loss. Then, by using the current value for the per unit heating energy cost, the annual energy cost of a boiling manhole can be obtained.

Although the sample calculations in the previous sections are not actual field data, they fall within appropriate ranges of typical flooded manhole conditions. Using a value of \$6.79 per MBtu (as obtained from the Army "Red Book" [FY94, Vol I] for the heating energy unit cost [Department of the Army 1994, p 4-16]) a simple cost analysis can be made. Tables 4 and 5 summarize the English units correlation results for each case, and reports the corresponding cost per year.

Table 4. Cost per year of a flooded manhole, high temperature hot water.

High Temperature Hot Water	Temperature (°F)	Length of Pipe (ft)	Outside Diameter (ft)	Velocity	Heat Loss (Btu/hr)	Cost per Year per ft (\$)	Cost per Year (\$)
Case 1	325.4	14	0.3333	4 ft/s	580,000	2,464	**34,499**
Case 2	296.6	23	0.3937	high	873,000	2,258	**51,926**
Case 3	278	11	0.25	medium	211,000	1,141	**12,550**
Case 4	365	19	0.5417	low	1,387,000	4,342	**82,499**

Table 5. Cost per year of a flooded manhole, dry steam.

Dry Steam	Pressure (psia)	Length of Pipe (ft)	Outside Diameter (ft)	Velocity	Heat Loss (Btu/hr)	Cost per Year per ft (\$)	Cost per Year (\$)
Case 5	130.53	14	0.3333	230 ft/s	1,432,000	6,084	**85,176**
Case 6	159.54	23	0.3937	high	2,710,000	7,008	**161,192**
Case 7	80	11	0.25	medium	500,000	2,704	**29,740**
Case 8	174.05	19	0.5417	slow	2,853,000	8,931	**169,698**

These figures provide a solid basis for decisions about the maintenance and repair of a flooded manhole. Some maintenance tasks, such as cleaning or unclogging drains, cost little or nothing (USACERL TR M-91/01, March 1991, pp 26-28). The cost to repair a flooded manhole can be nominal, ranging from as low as $300 to replace a sump pump to over $1000 to repair or seal portions of the manhole itself, based on calculations using the Department of Defense Renewables and Energy Efficient Planning (REEP) computer program (Nemeth, Fournier, DeBaille, et al. 1995). However, maintenance and repairs of flooded manholes are often not made because of budgetary or manpower limitations. Priority is often given instead to utility components perceived to have a higher need for immediate repair or replacement; that is, those that carry identifiable economic consequences if left uncorrected. Use of this methodology will produce results, as shown in Tables 4 and 5, that clearly illustrate the tremendous potential for energy loss and increased energy costs in a boiling manhole. Note that these costs are for individual manholes. The costs can increase dramatically if an installation, as is often the case, has a number of flooded manholes. By making it possible to estimate the losses from flooded manholes, an installation's operations and maintenance staff will be able to easily show the consequences of not performing maintenance and repairs to manholes that require it. Maintenance and repair payback calculations can also be easily and quickly made to justify the remedial measures required.

Besides the obvious waste of energy, there are additional economic costs associated with not maintaining and properly repairing manholes. The plant supplying the HTHW or the dry steam will have an artificially high heat demand. This will increase the cost of maintenance and repair on the facility as well as lower the life of the plant. There is also the potential that the system will not have the capacity to meet demand because of the large amount of energy loss in the distribution system. Because plants are designed to meet the maximum expected demand of the consumers, a large enough amount of energy loss the plant may compromise the plant's ability to provide sufficient amounts of heat to the fringe areas of a heat distribution system.

Although the model used to develop the correlations is based on well accepted and documented correlations and methods, there is still an unknown amount of error in the heat loss estimations as compared to any experimental data. However, even if the estimations by the heat loss correlations are off by 50%, the amount of heat energy lost is still substantial. To completely validate the correlations and to help quantify their error, it is recommended that a benchmark experiment be performed. Nevertheless, as stated above, even with a large error in the heat loss correlations, the energy lost in a boiling manhole has a large impact on the heat distribution system's performance.

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